


## RESEARCH ARTICLE

# Round-robin weathering test of various polymeric back-sheets for PV modules with different ultraviolet irradiation and sample temperatures

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## Abstract

Durability assessment of materials exposed to natural weathering with expected service lifetimes of more than 20 years requires accelerated testing of the UV stability, especially for polymeric materials. Fraunhofer ISE organized an interlaboratory comparison for testing different back-sheets in various test laboratories using different UV sources. The five participating test laboratories used three different types of UV sources. The interaction of the UV radiation with the polymers used in PV modules is main subject of this round-robin. Laminates were produced by using solar glass and a suitable EVA encapsulant combined with 10 different back-sheets. The simultaneous usage of different optical filters allowed to investigate roughly the spectral sensitivity and the intensity impact.

The degradation was followed by spectral reflectance and transmittance measurements and calculation of the yellowness index as degradation indicator. Clear differences in the degradation behavior of the different products were found.

## KEYWORDS

back-sheets, interlaboratory comparison, photovoltaic modules, test standards, UV sources, UV test

## 1 | INTRODUCTION

Photovoltaic modules are used for the conversion of solar energy to electricity. Durability testing of materials exposed to natural weathering requires testing of the UV stability, especially for polymeric materials. Numerous papers dealing with the two most prominent polymeric components, namely, the encapsulant of the cells and the weather-protecting back-sheet, can be found in the literature. The type approval testing of PV modules according to the standard IEC 61215 ed. 3 and IEC 61730 includes a so-called UV-preconditioning test with a total UV dose of 60 kWh/m<sup>2</sup>. About 3%–10% should be in the UV-B wavelength range (280–320 nm). However, the spectral distribution of the radiation source is very important to the degradation

because the samples show unique spectral sensitivities to the radiation applied. A filtered xenon light is the ideal artificial light source because of the sun-like spectrum. But, in addition to the high costs and relatively low efficiency, the use of a xenon light bears another disadvantage, namely, the fact that the samples are strongly heated up by the broadband irradiation from the UV to the infrared. Less than 6% of the intensity of solar radiation is in the UV range. In case of increasing the intensity of the light source for accelerating the UV test, the overheating of the samples would have to be prevented more strictly, and the temperature of the samples have to be measured in order to avoid misinterpretation of the test results.

Less temperature impact can be expected from UV-A fluorescent tubes, because they have an intensity maximum around 340 nm and

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decreasing with the longer wavelengths. However, they are limited in intensity and not an ideal solar simulator. Therefore, there remains the question whether the longer wavelength radiation (VIS-NIR) might cause degradation phenomena or contribute to degradation that could not be revealed by those UV tests.

Metal-halide lamps (HMI or HQI) are very powerful light sources used as solar simulators or UV sources if the spectral similarity to the natural sun light is not required. Their strong narrow-banded emission lines, however, need careful interpretation of material degradation by taking into account the spectral sensitivity of the materials.

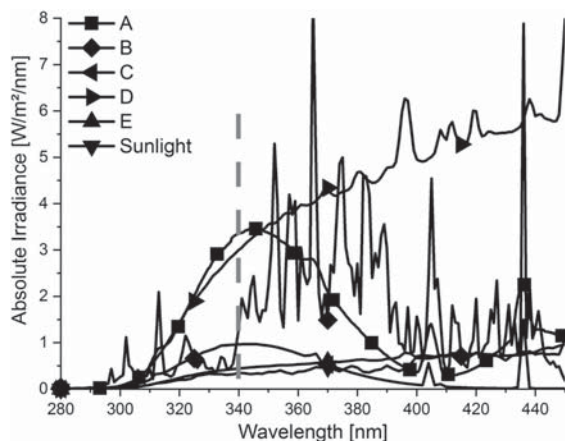
Fraunhofer ISE performed an interlaboratory comparison of UV testing in five test labs using the products of various back-sheet manufacturers in order to evaluate the differences in the durability test results caused by the use of different UV sources, different spectral ranges, different sample temperatures and to find methods for investigating the degradation kinetics. This work compliments that of a group directed by NREL (USA) focused on the UV testing of encapsulants.<sup>1</sup>

Meanwhile, the Working Group 2 of the IEC Technical Committee 82 elaborated a technical description of material characterization<sup>2</sup> and testing<sup>3</sup> for polymeric materials for photovoltaic modules (IEC 62788). Part 2 is dedicated to polymeric front and back-sheets.

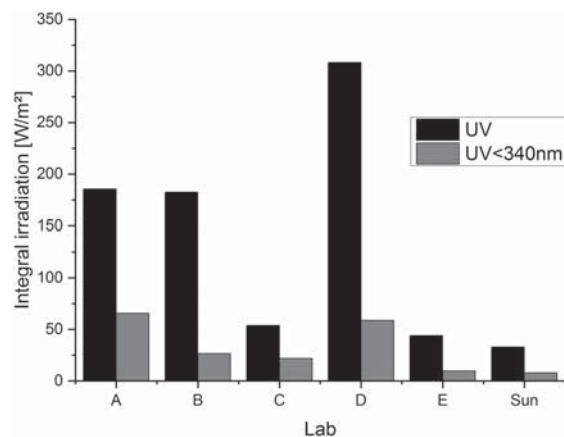
## 2 | EXPERIMENTAL SETUP

### 2.1 | UV sources

The five participating laboratories from Taiwan (ITRI), Korea (FITI), the United States (Atlas-Ametek and NREL), and Germany (ISE) applied different light sources (see Figure 1): (A and C) fluorescent lamp fields, (B) metal halide, (D) 10× xenon, and (E) 1× xenon. The obvious differences are the smooth spectra of the fluorescence lamps and the xenon arcs and the emission bands of the metal-halide lamp (see Figure 1).



**FIGURE 1** Spectral irradiance of a selection of different UV light sources in the participating labs and natural UV irradiation for AM1.5



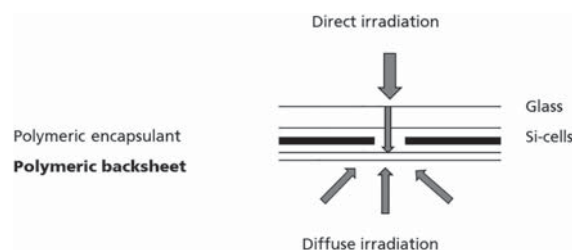
**FIGURE 2** Integrated spectral irradiation of a selection of different UV light sources in the participating labs and natural UV irradiation for AM1.5

The emission spectra allow the integration of the UV range (280–400 nm) and the photodegrading short wavelength range below 340 nm (see Figure 2) that might be more accurate than integral UV measurements.<sup>4</sup> One big problem is the application of integral UV sensors for controlling the UV dose because they are mostly calibrated with other types of light sources like sun or tungsten-halogen lamps and have different spectral sensitivities at the long wavelength edge (400 nm) as was found in a previous comparison of various UV sources for material testing.<sup>4</sup>

### 2.2 | Sample design

The focus of the round-robin testing was put on polymeric back-sheets of photovoltaic modules. They are hit by direct UV radiation from the normally light-facing glass side, which is filtered by the front-glazing and the polymeric encapsulant as in the gap between the solar cells (in case of modules with silicon solar cells) or unfiltered by diffuse UV radiation from the back side (see Figure 3).

Measurements of the spectral UV radiation on Canary Island resulted in a ratio of 5% to 10% of radiation on tilted or vertical back-side compared with the front in plane of array (tilt angle of 22.5° to the south corresponding to the latitude and roughly 1 m above the

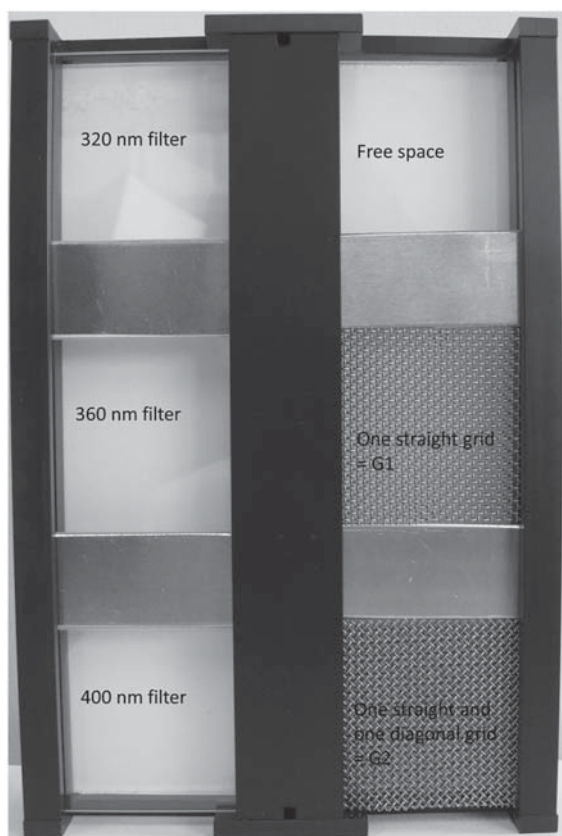


**FIGURE 3** Sketch of the design of a photovoltaic module with a polymer back-sheet

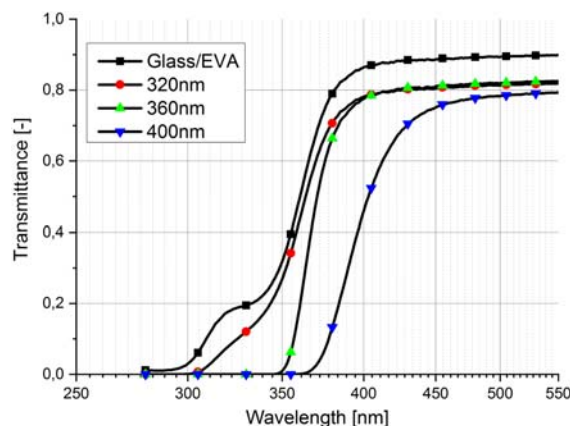
natural reddish ground). The yearly loads of UV radiation at the Canary Island test site are described elsewhere.<sup>5</sup>

Sample laminates were produced with the same solar glass from Interfloat GmbH and the same encapsulant (Bridgestone S18) but without solar cells and 10 different back-sheet materials. Some of the back-sheets had a weak UV stability in order to facilitate degradation investigation by the accelerated life tests. Therefore, the industry partners did not want to disclose the composition of the test samples. They were exposed with the front side and with the back side towards the UV source, separately. The size of the samples (200 mm × 130 mm) was selected in order to allow the partial cover with spectral long-pass edge filters and neutral density filters for simultaneous variation of the UV irradiation spectrally and with intensity (see Figure 4).

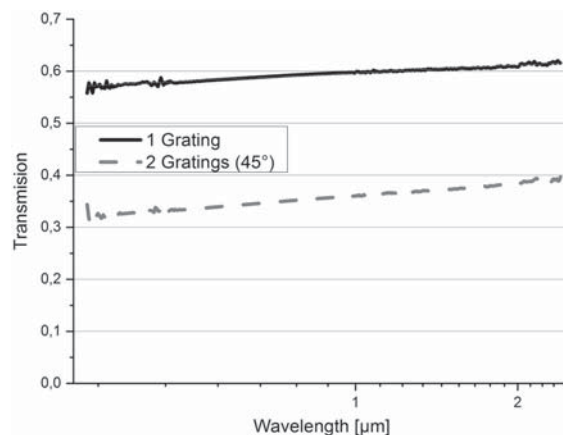
The spectral transmittance of the edge filters (Figure 5) is to be multiplied with the transmittance of the glass cover and the encapsulant allowing the calculation of the irradiation on the normally light-facing (front) side of the back-sheet in the laminate. Gratings that were used are a less expensive alternative for neutral-density filters. The effect of a single grating and two stacked gratings can be seen in Figure 6. The spectral transmittance is sufficiently wavelength independent for the wavelength range of interest. The integral UV transmittance is 56% for the single grating and 32% for crossed gratings.



**FIGURE 4** Sample holder with edge filters (left column) and intensity filters (gratings on the right side) and uncovered part (right top)



**FIGURE 5** Hemispherical transmittance of the glass/encapsulant and additional edge filters [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



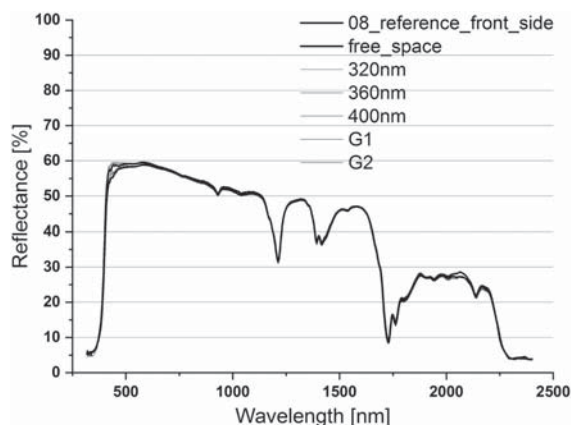
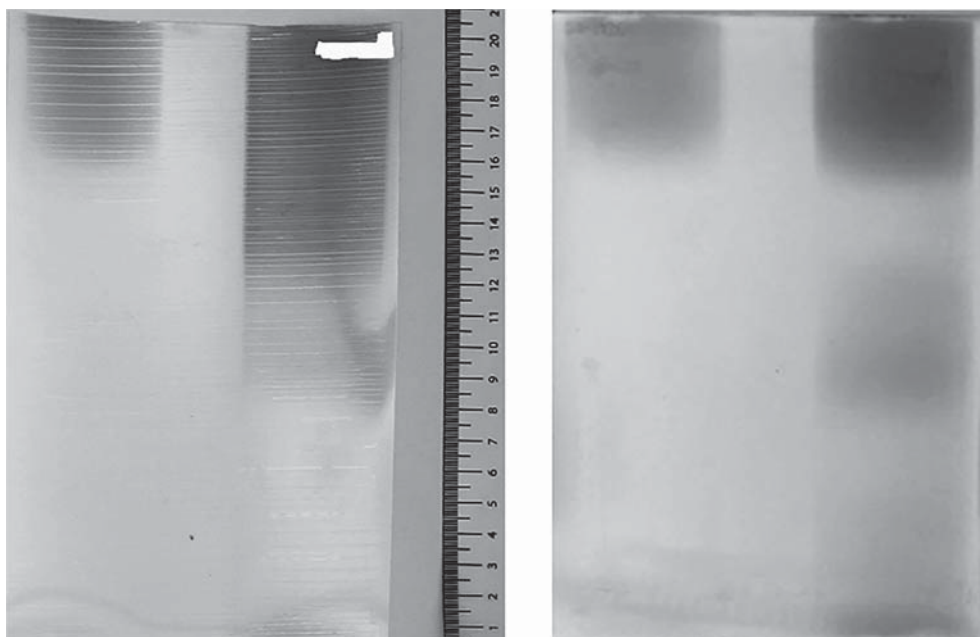
**FIGURE 6** Hemispherical transmittance of the grating filters

The effect of the filters could be seen visually as different yellowing or even blistering (see Figure 7). Therefore, the yellowness index (YI) seems to be an appropriate degradation indicator. It has been shown that YI can be correlated with the mechanical properties (strain to break) of polymeric foils.<sup>6</sup>

### 2.3 | Degradation indicator

Most of the back-sheet samples were filled with diffusely reflecting inorganic compounds (usually TiO<sub>x</sub>). The spectral hemispherical reflectance was measured with an integrated sphere from the irradiated side (front or back). Extremely stable samples show hardly any changes of the spectral reflectance of sample spots behind the applied filters after 120 kW/m<sup>2</sup> UV irradiation (see Figure 8), proving that the used EVA and the glass were not degraded by the UV exposure. Another example (shown in Figures 7 and 9) shows the yellowing of a sample depending on the applied filters.

**FIGURE 7** Two samples with yellowing and blistering depending on the filters and uncovered part (right upper corner)



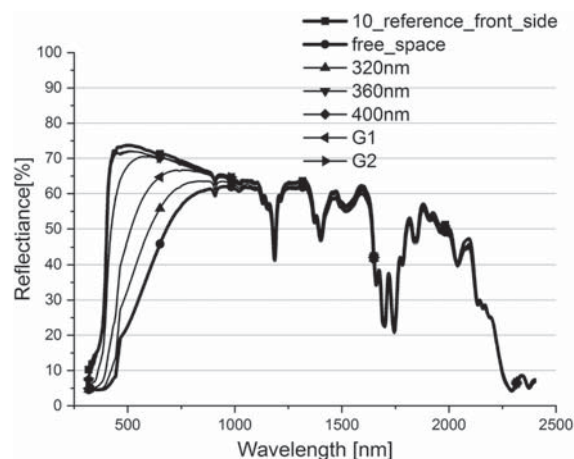
**FIGURE 8** Reflectance of Sample Number 8 of the glass/encapsulant behind additional edge and grey filters after 120 kW/m<sup>2</sup> irradiation at 60°C

Color coordinates X, Y, and Z were calculated from the spectra and used for the computation of YI with the following formula according to ASTM E313<sup>7</sup>:

$$YI = 100(C_X X - C_Z Z) / Y \quad YI = 100(C_X X - C_Z Z) / Y$$

with  $C_X = 1,2871$  and  $C_Z = 1,0781$ .

The changes of YI are used to compare the degradation of the different samples, various test labs, and the different irradiation conditions. The YI was used as a degradation indicator for comparison of the dose-response functions showing relatively big differences between the samples and the labs; see Figures 10–14. The small differences for stable samples indicate that no big systematic deviations in the YI evaluation of the labs are expected. The two less stable



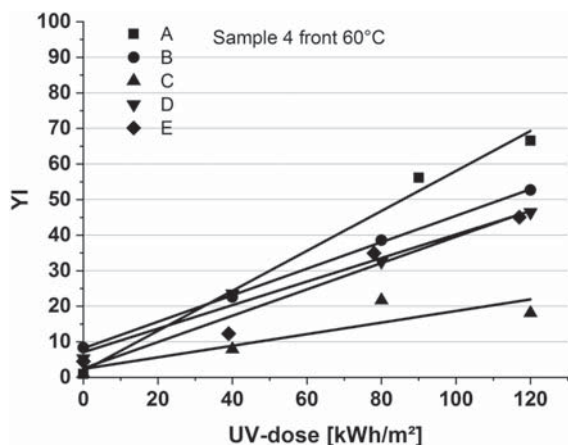
**FIGURE 9** Reflectance of the sample number 10 of the glass/encapsulant behind additional edge and grey filters after 120 kW/m<sup>2</sup> irradiation at 60°C

samples exhibit dramatic discrepancies of the results. The differences increase with dose as shown in Figure 10. This is tentatively attributed to measurement of the irradiation and differing sample temperatures. Sample temperatures were not controlled in this experiment, because some of the test cabinets rotate the samples in carousels around the radiation sources and in order to keep the effort low. One lab investigated the sample temperatures below the different filters in various test cabinets (see below).

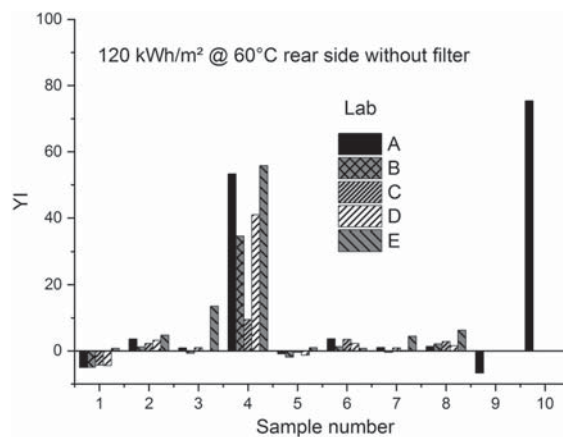
### 3 | RESULTS

The difference of the YI of the samples after 120 kWh/m<sup>2</sup> UV irradiation (corresponding to about 2 years outdoor exposure<sup>3</sup>) is shown in Figure 11 for the EVA (front) side of the laminates and in Figure 12

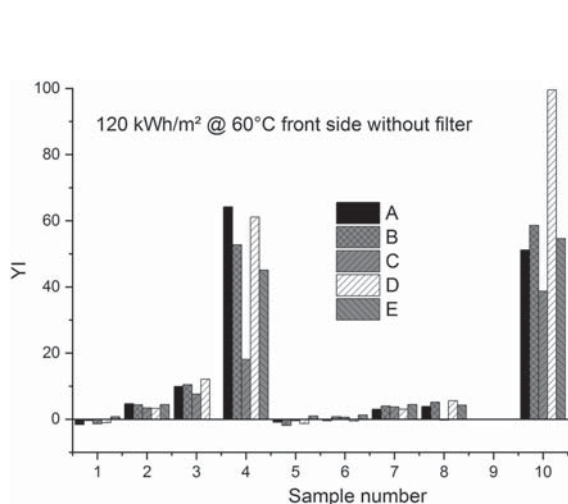




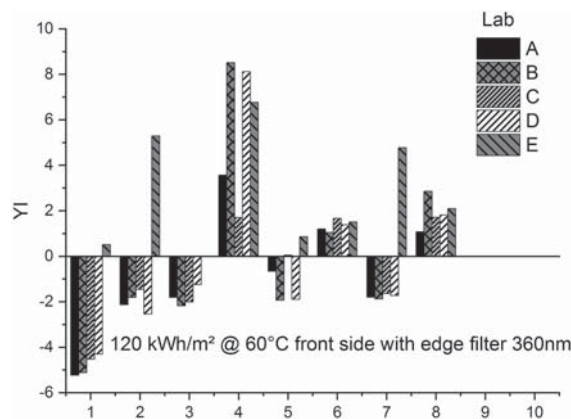
**FIGURE 10** Yellowness index of Sample Number 4 aged through the glass/encapsulant front side as a function of the UV dose till 120 kWh/m<sup>2</sup> irradiation at 60°C



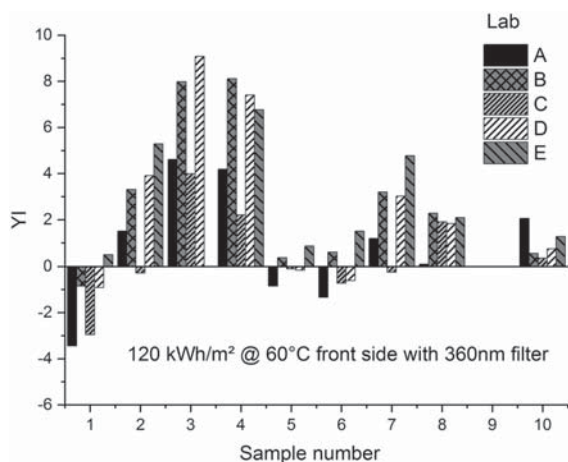
**FIGURE 13** Yellowness index results (air side) without filters after 120 kWh/m<sup>2</sup> from five different test labs



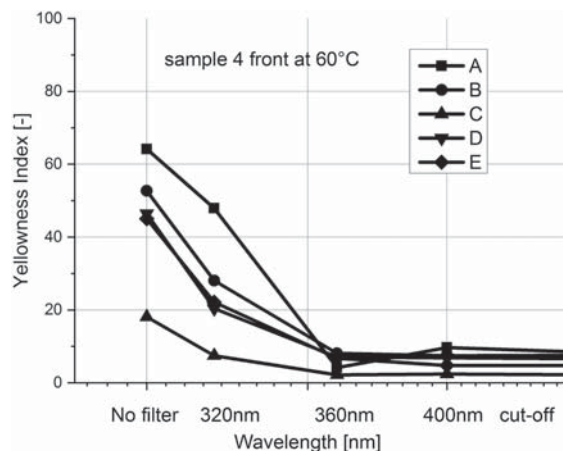
**FIGURE 11** Yellowness index results (front side) without filters after 120 kWh/m<sup>2</sup> from five different test labs



**FIGURE 14** Yellowness index results (air side) after 120 kWh/m<sup>2</sup> behind the 360-nm edge filters from five different test labs

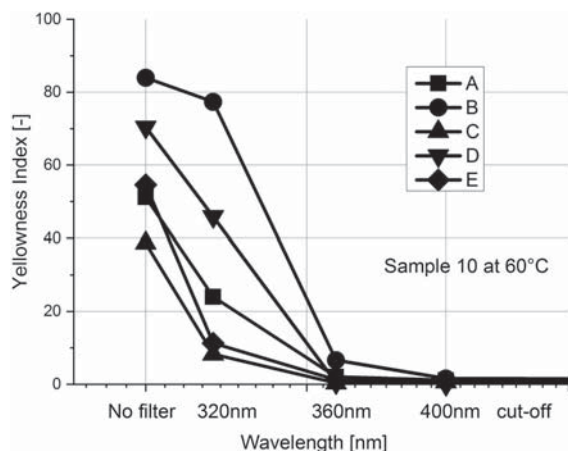


**FIGURE 12** Yellowness index results (front side) after 120 kWh/m<sup>2</sup> behind the 360-nm edge filters from five different test labs

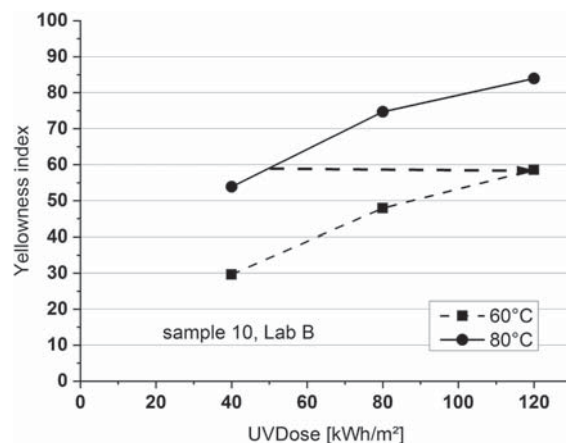


**FIGURE 15** Yellowness index results of Sample 4 (front side) behind the edge filters after 120 kWh/m<sup>2</sup> from five different test labs

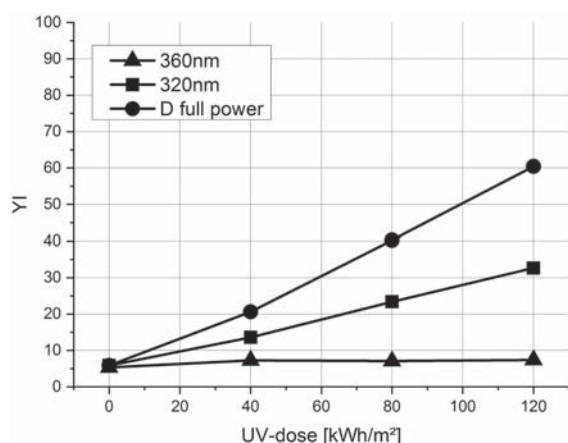
for the back-side of the back-sheets. A number of samples without degradation of the optical appearance as indicated by YI are found. Only Sample 4 and Sample 10 showed clear increase in YI. The



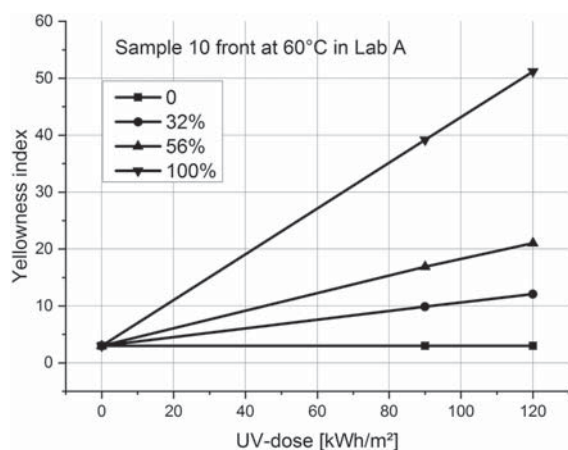
**FIGURE 16** Yellowness index results of Sample 10 (front side) behind the edge filters after 120 kWh/m<sup>2</sup> from five different test labs



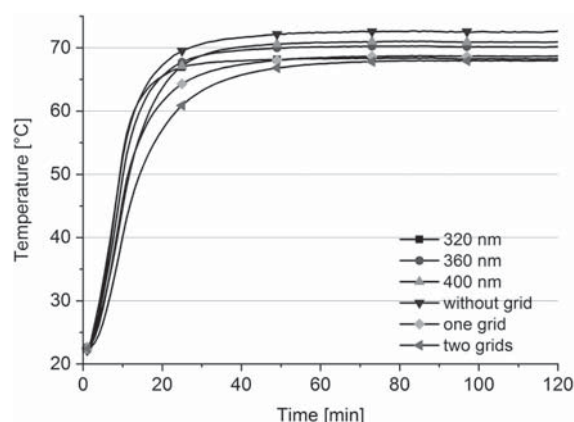
**FIGURE 19** Yellowness index results of Sample 10 (front side) as function of the UV dose at 60°C and 80°C in Test Lab B



**FIGURE 17** Yellowness index of the rear side of back-sheet No. 4 in Lab D at 80°C without and with the filter (320 and 360 nm) as function of the UV dose



**FIGURE 18** Yellowness index results of Sample 10 (front side) as function of the UV dose at 60°C with and without grey filters in Test Lab A



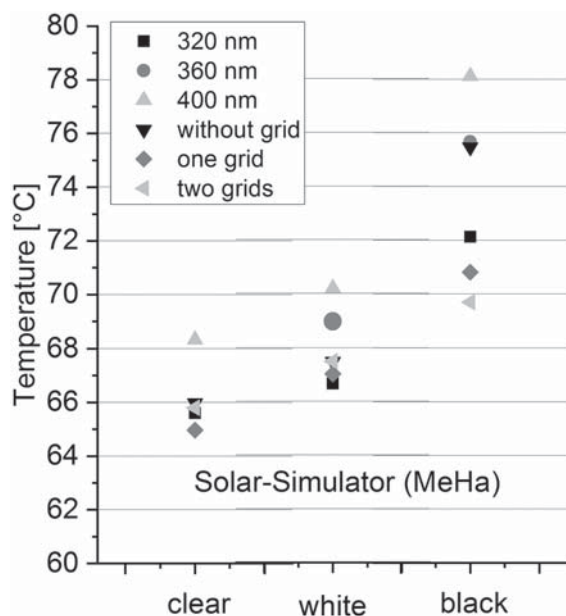
**FIGURE 20** Progress of the sample temperatures below the various filters of a horizontally oriented black back-sheet at 60°C cabinet temperature under irradiation with an HQL-UV source

difference between the minimum and maximum degradation was around 100% for the data in Figure 11 and 120% for Figure 12 for tests without filter and with the 360-nm edge filter, respectively.

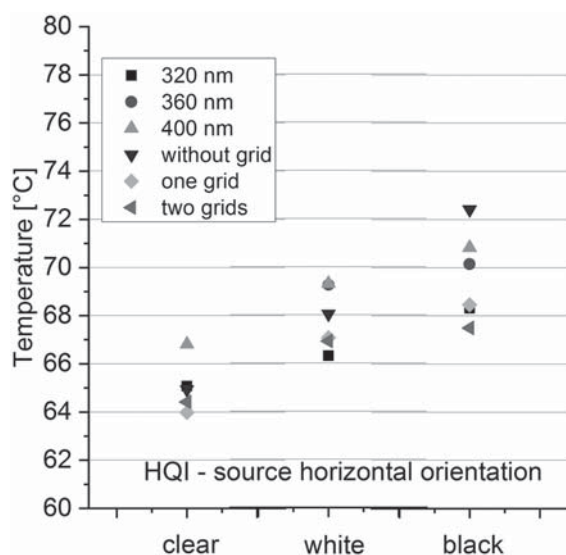
The results of the samples behind the edge filters (360 nm cutoff) are shown in Figures 12 and 14. Note the factor of 10 in the scaling of the y-axis taking into account the one magnitude less degradation, when filtering out the short wavelength range of the irradiation. This effect can be seen in all labs, whereas the cutoff at 320 nm has different effects in the different labs (Figures 15 and 16). The two samples 4 and 10 behave differently because of their different spectral sensitivity.

Figure 17 shows the degradation as function of the dose behind the edge filters. Similar curves can be found for the degradation of the samples behind the grating filters (Figure 18). The constant degradation ratio proves a linear relation between YI and the UV dose.

The temperature dependence can be seen clearly in Figure 19. An acceleration factor of 2.4 could be achieved by a temperature increase of 20 K. This result underlines the necessity of controlling the sample



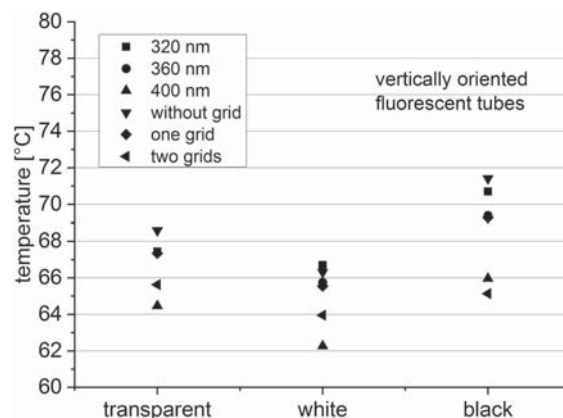
**FIGURE 22** Sample temperature of three differently colored back-sheets at 60°C cabinet temperature after 60-min irradiation with an HMI solar simulator



**FIGURE 21** Sample temperature of three differently colored back-sheets at 60°C cabinet temperature after 60-min irradiation with an HQI-UV source

temperature carefully, especially when the sample coloration leads to a high absorptivity of the irradiation and when the irradiation covers a bigger part of the spectrum at longer wavelengths than needed for photo degradation (e.g., solar simulators).

Samples equipped with thermocouples below each filter position were placed horizontally below a UV-enhanced metal-halide lamp (HQI) or a solar simulating metal-halide lamp (HMI) in climatic cabinets at 60°C cabinet temperature. Temperature equilibrium was



**FIGURE 23** Sample temperature of three differently colored back-sheets at 60°C cabinet temperature after 60-min irradiation with a fluorescent tube UV source

reached after 60 min (see Figure 20). The highest temperatures and the biggest deviation from the set cabinet temperature (60°C) between 70°C and 78°C were measured with the solar simulator for the blackened sample, of course, while the transparent (least absorbing) samples reached 65°C to 68°C at 60°C cabinet air temperature (see Figure 22), while the UV-enhanced lamp remained below 72°C (Figure 21). Even lower deviations were found for vertically mounted samples in front of fluorescent tubes (Figure 23). In all cases, temperature spreads of 3 K to 8 K were found depending on the filter and the color.

## 4 | CONCLUSION

The comparative testing of laminates with different back-sheets under UV light allows the identification of insufficiently durable samples. The yellowness index differentiated the samples by a factor of around 100. The changes of the yellowness index as function of the UV-dose showed differences up to a factor of 3 between the 5 participating labs. The reason could be differences of the spectral UV-irradiation, and of the sample temperature, or errors in the control UV measurements yielding different degradation acceleration. Edge filters for assessment of the spectral sensitivity showed that degradation was not caused by radiation with longer wavelengths than 350 nm. Metal gratings can be used as grey filters for simultaneous testing of the degradation as function of the intensity allowing the investigation of the reciprocity. Testing at different sample temperatures offers the possibility of acceleration of the photodegradation by temperature increase on one hand and shows the importance of measuring the sample temperature during irradiation on the other hand. Errors in the degradation process evaluation must be expected, especially when the optical properties of the sample enable a high absorption of the light. A further evaluation of the test results is subject of a following publication.<sup>8</sup>

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